An Imaging System for Satellite Hypervelocity Impact Debris Characterization

Matthew Moraguez, Dr. Kunal Patankar
University of Florida
Dr. Norman Fitz-Coy
University of Florida
Dr. J.-C. Liou
NASA Johnson Space Center
Dr. Heather Cowardin
UTEP/JACOBS

ABSTRACT

This paper discusses the design of an automated imaging system for size characterization of debris produced by the DebriSat hypervelocity impact test. The goal of the DebriSat project is to update satellite breakup models. A representative LEO satellite, DebriSat, was constructed and subjected to a hypervelocity impact test. The impact produced an estimated 85,000 debris fragments. The size distribution of these fragments is required to update the current satellite breakup models.

An automated imaging system was developed for the size characterization of the debris fragments. The system uses images taken from various azimuth and elevation angles around the object to produce a 3D representation of the fragment via a space carving algorithm. The system consists of N point-and-shoot cameras attached to a rigid support structure that defines the elevation angle for each camera. The debris fragment is placed on a turntable that is incrementally rotated to desired azimuth angles. The number of images acquired can be varied based on the desired resolution. Appropriate background and lighting is used for ease of object detection. The system calibration and image acquisition process are automated to result in push-button operations. However, for quality assurance reasons, the system is semi-autonomous by design to ensure operator involvement. This paper describes the imaging system setup, calibration procedure, repeatability analysis, and the results of the debris characterization.

1. INTRODUCTION

In order to ensure satellite mission success, orbital collisions must be avoided through space situational awareness. The collision threat is intensified by the growing orbital debris population, which is largely made up of fragmentation debris [1]. Debris fragments as small as 1 cm can cause catastrophic damage to a satellite. The ability to track this orbital debris is essential to avoid collisions. However, only objects 10 cm and larger are currently tracked. Thus, satellite breakup models are needed to predict the behavior of fragments that are too small to be tracked, yet are large enough to pose a threat [2].

The collision of Cosmos-2251 and Iridium-33 in 2009 showed that NASA's current satellite breakup model needed to be updated to accurately predict the breakup of modern satellites [3]. The DebriSat project was undertaken to update satellite breakup models to reflect new materials and processes used in satellite design and construction. A representative 50 kg LEO satellite, DebriSat, was subjected to a hypervelocity impact test simulating an orbital collision. The debris fragments were collected and are currently in the process of being characterized [4].

One of the ways that satellite breakup models characterize fragments is by size. The standard parameter for size characterization of orbital debris used by NASA is characteristic length. Characteristic length is defined as the mean of an object's three maximum orthogonal projected lengths. This provides a single length parameter used to describe the size of a fragment. Originally, characteristic length was measured by hand using calipers and graph paper. This measurement approach was time-consuming and relied on inconsistent human measurement. The next improvement in measurement was to utilize a 3D scanner and manually measure the resulting model in computer software. While this improved repeatability and traceability, the human factor was still present in measurements and the process took hours per object [5]. The automated imaging system that has been developed will provide quick, accurate, and repeatable characteristic length measurements. This paper discusses the imaging system hardware used to acquire the images that will be used for 3D reconstruction and measurement of an object.

2. IMAGING SYSTEM SETUP

2.1 Imaging System Overview

The intent of the imaging system is to provide an automated means of measuring the characteristic length of an object. The process is divided into three phases: image acquisition, 3D reconstruction, and characteristic length measurement. The image acquisition aspect of the system is the focus of this paper. This includes the physical setup that is used to capture images of the object to be measured. The 3D reconstruction aspect, which is discussed in [6], includes the process that produces a 3D point cloud representation of the object from the numerous acquired images of the object. This involves detecting the object in each image and utilizing a space carving algorithm to construct a 3D representation. Once the 3D point cloud representation is generated, a characteristic length algorithm, which is described in [7], is used to automatically extract the characteristic length of the object. This characteristic length is then uploaded to a database for storage.

2.2 Image Acquisition Instrumentation

This imaging system has the instrumentation necessary to acquire images from various azimuth and elevation angles around the object. These images will then be used to generate a 3D point cloud of the object. As shown in Fig. 1, the system currently features six point-and-shoot cameras, a rigid support structure, a rotary turntable, a green screen background, and diffuse lighting. The system also features a desktop computer to automate image acquisition, detect the object in images, perform 3D reconstruction via a space carving algorithm, measure the characteristic length of the point cloud, and store the images and measurement results. A detailed view of the cameras and support structure is shown in Fig. 2. The cameras, which are equidistant from the center of the turntable, are rigidly fixed to the support structure to preserve calibration. Images can be acquired from around the object by rotating the turntable to various azimuth angles while acquiring images from various elevation angles. The green screen and diffuse lighting are used to aid in object detection in the images.

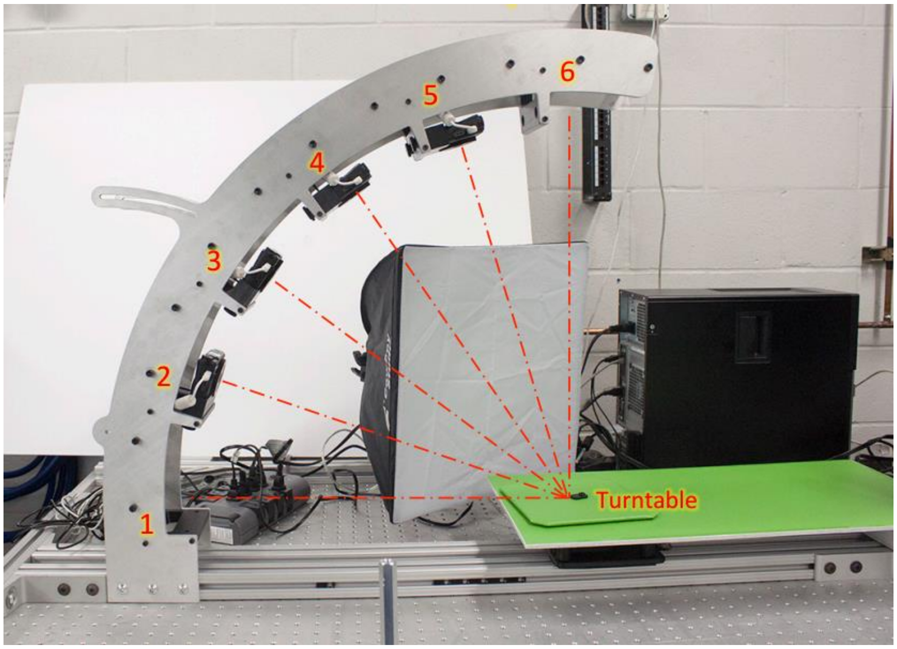

Fig. 1. The imaging system setup is shown above. The debris fragment can be seen on the green screen turntable. Six cameras view the object from different elevation angles. However, the image shown is an early configuration with only four cameras mounted.

Fig. 2. Four of the point-and-shoot digital cameras used in the system are shown above. They are rigidly mounted to the support structure. The white cable connected to each camera allows for computer automation of image acquisition. To eliminate the need for recharging the cameras, the battery in each camera has been replaced with an external power source.

In order to create a 3D representation, the object must be detected in each acquired image. To aid with object detection, a green screen background and diffuse lighting are used (Fig. 3). The green screen provides a background against which the object can be easily distinguished. The diffuse lighting is used to eliminate shadows in the images. The system has proven capable of detecting objects that are partially reflective and ones that are as small as 2 mm in length. A sample object image is shown in Fig. 4.

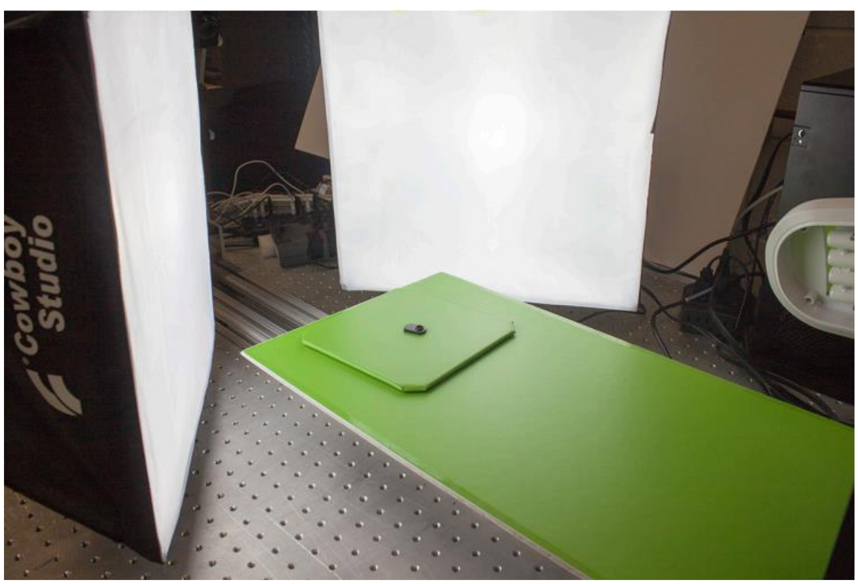

Fig. 3. The green screen background, diffuse lighting, and turntable are shown in the image above. The diffuse lighting is used to eliminate shadows that interfere with object detection in images. The green screen also improves object detection against the background. The object rests on a turntable that rotates incrementally through one full rotation during imaging.

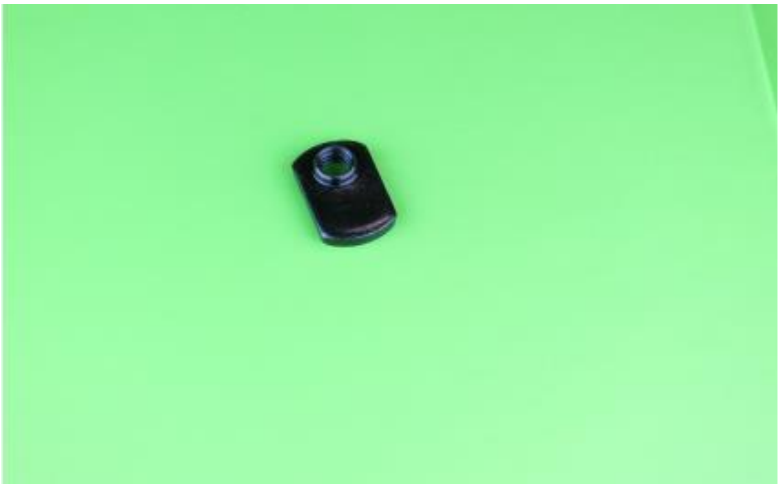

Fig. 4. The image of a test sample is shown above. The object is automatically detected in the image. Effective object detection depends on appropriate lighting and background. Numerous images, taken from various elevation and azimuth angles, are then reconstructed into a 3D representation using a space carving algorithm.

2.3 System Operation

An algorithm that automates the image acquisition process was developed. Through a single command from the user in the graphical user interface (see Fig. 5), images from each elevation are acquired, the turntable is incremented to the next azimuth, and the process is repeated until images from all azimuth positions are acquired. The system is controlled such that the turntable increments to the next azimuth angle only once all cameras have acquired images from each of their elevation angles. Currently, images are acquired at six elevation angles and 21 azimuth angles. The first and last azimuth angles are made to be the same. As a result, the first and last image for each camera can then be compared to confirm that the object has not moved during imaging. The turntable acceleration is limited to reduce the risk of object movement relative to the turntable during imaging, which would reduce accuracy. It takes about four minutes to acquire the 126 images currently used for 3D reconstruction.

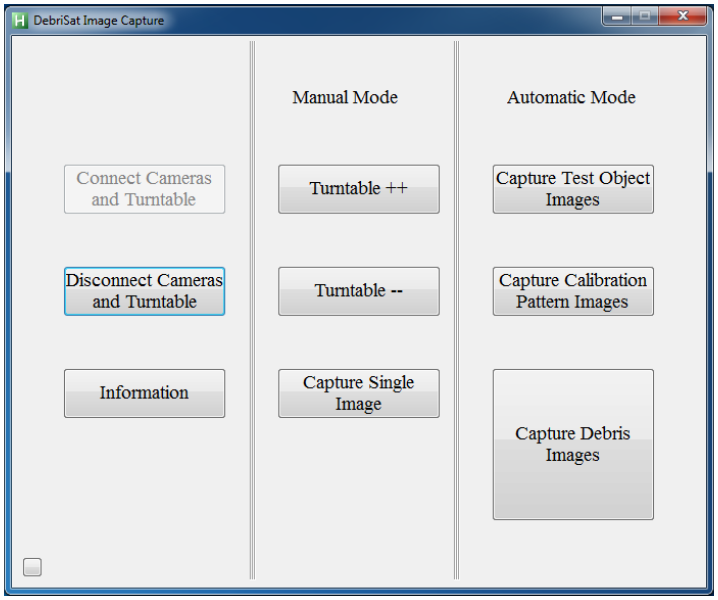

Fig. 5: The graphical user interface (GUI) shown above allows the operator to acquire images of the object by simply clicking the "Capture Debris Images" button.

3. CAMERA CALIBRATION

In order to reconstruct the images into a single 3D representation, the imaging system must be calibrated. Camera calibration is performed by acquiring images of a calibration checkerboard pattern of known size (see Fig. 6). The automated imaging sequence is run to acquire images from each azimuth and elevation angle. These images are then processed to detect the corners in the checkerboard pattern. Once the corners are detected in each image, the extrinsic and intrinsic parameters for each of the cameras are extracted. Using the extrinsic parameters, which give location and orientation information for the cameras, the images can be reconstructed into a single 3D representation of the object. Using the intrinsic parameters, the object size in the image can be related to its physical size. With a rigid camera setup and a precise turntable, the calibration will still be valid after numerous objects are imaged. Testing will be conducted to experimentally determine the number of cycles over which calibration is preserved. The system must be calibrated to within the desired measurement accuracy for all objects imaged. When the imaging system is in use, calibration will be required after a fixed number of objects are imaged. At the very least, calibration will be conducted at the beginning of every day regardless of the number of objects processed the previous day. In addition, a calibration sphere of known diameter (Fig. 7) will be imaged to ensure the measurement results are within the required accuracy.

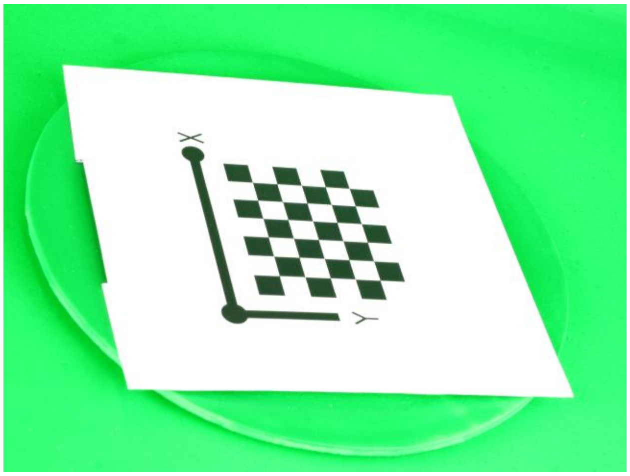

Fig. 6. The pattern above is used for calibration of the imaging system cameras. The checkerboard corners are detected to extract the extrinsic and intrinsic parameters for each image.

Fig. 7. The calibration sphere shown above is used to ensure accuracy of the imaging system measurements. The sphere, which has a known diameter, is imaged after calibration to ensure that the measurement is within the required accuracy threshold.

4. PERFORMANCE

This imaging system was developed for size characterization of debris fragments from the DebriSat project. With the system, an object’s characteristic length can be quickly and accurately determined. The system is fully automated to eliminate the human factor from measurements. The non-contact measurements also reduce fragment handling and the risk of fragment damage.

The imaging system is intended to generate a 3D point cloud representation of the object from which maximum dimensions and characteristic length can be extracted. A space carving algorithm is used to accomplish 3D reconstruction from the silhouette of the object seen in images taken from various azimuth and elevation angles around the object. The use of the silhouette for reconstruction ensures that the maximum dimensions are captured. In addition, the space carving approach reduces processing time by disregarding features that are irrelevant for characteristic length measurement. For this reason, the space carving approach does not detect concave features in faces of the object. However, these concavities are irrelevant for characteristic length measurement.

A variety of test samples have been processed using the imaging system. The samples tested have varied in size from maximum dimensions of 2 mm to 100 mm. The test objects have had a variety of shapes, colors, and reflectivities. The results from one of the test samples processed is shown in Fig. 8 and Fig. 9. Currently, objects with characteristic lengths as small as 2 mm can be imaged and detected. The characteristic length results have shown an accuracy of about 2% and a repeatability of about 1.5%. These accuracy and repeatability values will be refined as further testing is completed. The measurement accuracy was verified through comparison with existing approaches for characteristic length measurement, such as hand measurements with calipers and NASA 3D scanner measurements. The measurement results were also compared to the known dimensions of computer-generated point clouds. In order to measure repeatability, the imaging system was used to measure the same object repeatedly. The imaging system improves repeatability by eliminating the human factor from measurements.

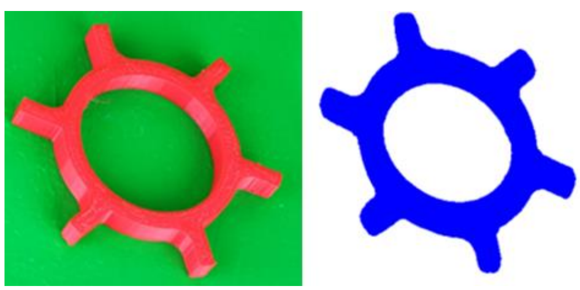

Fig. 8. The original test sample image is shown on the left. The 3D point cloud representation of the object is shown on the right.

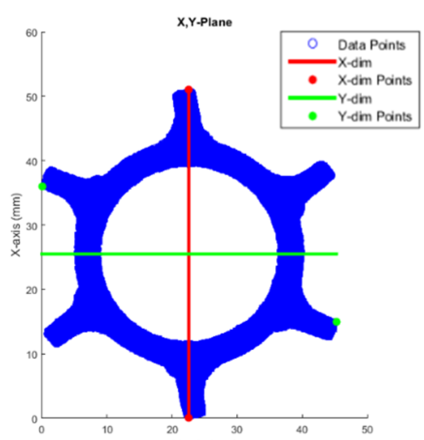

Fig. 9. The X-dim (51.0 mm) and Y-dim (45.3 mm) measurement result for the test sample is shown above. The characteristic length algorithm measures the point cloud and the results are plotted for traceability and operator oversight.

5. FUTURE WORK

Future work will be aimed at further developing the imaging system capabilities and ease of use. Currently, the operator is required to manually detect the four corners of the checkerboard pattern in each image for calibration. The calibration parameters are then calculated automatically from these manually detected corners. Work is currently focused on implementing a fully automated checkerboard detection algorithm that does not require manual corner detection. While this would improve the speed and ease with which calibration can be conducted, it would not improve the debris imaging process since calibration is performed occasionally (not with each fragment imaged). Future work for camera calibration will also involve implementing a calibration cube, with checkerboard patterns on each face, to ensure that all cameras can see at least one calibration pattern at all times.

Future work will include processing more test objects to further validate the accuracy and precision of the imaging system. The possibility of acquiring an "optimal" number of images will be investigated. The optimization would involve minimizing the number of images required while still obtaining the desired measurement accuracy. This would reduce the image acquisition time and the computer memory required for image storage.

6. CONCLUSION

A fully automated imaging system has been developed for characteristic length measurement of DebriSat hypervelocity impact fragments. The imaging system is currently capable of acquiring a total of 126 images from six elevation angles and 21 azimuth angles. This image acquisition process can be completed with a single button-click and only takes about 4 minutes. Once these images are acquired, a 3D representation of the object can be generated and measured in about 2 minutes. Thus, the imaging system provides a complete approach for producing a 3D representation of an object from which characteristic length can then be measured.

This imaging system provides several advantages over alternative approaches to characteristic length measurement, such as using 3D scanners or calipers. The system obtains non-contact measurements and minimizes fragment handling to avoid damage or contamination of the object. In addition, the system acquires measurements of an object in about 6 minutes. These measurements are accurate and precise due to the elimination of the human factor from the measurement process. The system has a measurement accuracy of about 2% and a repeatability of about 1.5%. The complete automation of the system allows fragments to be processed quickly with minimal operator involvement. The imaging system will be used to process the tens of thousands of debris fragments generated in the DebriSat test.

7. ACKNOWLEDGMENTS

The DebriSat project is funded by the NASA Orbital Debris Program Office and the Air Force Space and Missile Systems Center.

8. REFERENCES

1. Osiander, R., and Ostdiek, P., "Introduction to Space Debris," *Handbook of Space Engineering, Archaeology, and Heritage*, CRC Press, Boca Raton, FL, 2009, pp. 363-379.
2. Englert, C., et al., "Optical Orbital Debris Spotter," Acta Astronautica, Vol. 104 (2014), pp. 99-105.
3. Werremeyer, M., et al., "Design and Fabrication of DebriSat – A Representative LEO Satellite for Improvements to Standard Satellite Breakup Models," 63rd IAC Congress, Naples, 2012, IAC-12,A6,3,7,x16098.
4. Rivero, M., Edhlund, I., et al., "Hypervelocity Impact Testing of DebriSat to Improve Satellite Breakup Modeling," 65th IAC Congress, Toronto, 2014, IAC-14-A6.2.10x25834.
5. Hill, N. M., and Stevens, A., "Measurement of Satellite Impact Fragments," NASA Orbital Debris Quarterly News, Vol. 12, No. 1, Jan. 2008, pp. 9-10.
6. Moraguez, M., et al., "An Imaging System For Automated Characteristic Length Measurement of DebriSat Fragments," 66th IAC Congress, Jerusalem, 2015, IAC-15-A6.1.x30288.
7. Moraguez, M., "An Algorithm for Characteristic Length Measurement from Point Cloud Data," AIAA Student Conference, Savannah, GA, 2015.